12MV-0008

A Novel Approach for Combat Vehicle Mobility Definition and Assessment

Macam S Dattathreya[1], Harpreet Singh[2]
[1]TARDEC, Warren, MI, [2] Wayne State University, Detroit, MI

ABSTRACT

Mobility assessment for combat vehicles is often a great challenge for the military due to various subjective attributes. The attributes' characteristics vary significantly depending on the vehicle type and its operating environments such as terrain, weather, and human factors. A clear definition and relationship between multiple attributes including human factors is necessary to assess mobility. To the best of authors' knowledge, many existing mobility assessment techniques use complex analytical methods and focus on individual attributes. In this paper, for the first time, the authors propose a novel approach to define vehicle mobility and its influencing attributes using qualitative linguistic fuzzy variables, which are defined as having values between 0 and 1. The authors also propose a fuzzy logic mobility (FLM) model and a simulation approach to assess a combat vehicle's mobility.

INTRODUCTION

Vehicle mobility is a subjective and broader term used to represent a vehicle's characteristics or dynamics. In other words, it is a vehicle's capability to move over a specified terrain, which is influenced by other environmental conditions such as weather. Mobility is a vehicle's ability to reach its destination by overcoming all hindrances such as weather and operating environments in addition to varying terrain. In other words, mobility describes how fast a vehicle can drive, how efficiently it can traverse various terrains, and how its propulsion and suspension systems behave while moving. For example, the mobility of a combat vehicle (CV) can be defined using maximum vehicle speed on paved roads, cruising range on snowy paved roads, and towing capability up a 20% slope. Generally, mobility engineers establish a set of attributes that influence a CV's mobility, perform complex mathematical calculations, determine numerical values, and inspect and correlate each value to other values that define a vehicle's mobility.

The mobility assessment of a CV is one of the key tasks necessary before fielding any vehicle, especially one potentially engaged in combat operations. The mobility assessment starts with a pre-defined mobility requirement with a set of attributes appropriate for the intended mission. Normally, mobility engineers develop CV simulation models to understand, assess, and analyze a vehicle's mobility. Simulation models are a necessary tool to minimize a vehicle's development cost and time. Each CV has its unique attributes, which influence its mobility. Patrick et al. propose a virtual modeling and simulation [1] suite for evaluating a CV's mobility under all expected terrain and weather conditions [1]. The Army has used NATO Reference Mobility Model (NRMM) [2] for mobility analysis. The NRMM simulation depends on empirical data, has range limitations, and does not have an adequate model to handle high mobility vehicles on urban and complex terrains. The NRMM requires a lot of effort to build a complete vehicle model before using it to assess mobility. Often, mobility engineers develop homegrown tools such as spreadsheets or software applications to assess a CV's mobility.

We need an approach to define and assess a CV's mobility and allow both engineers and non-engineers to understand and compare the mobility of multiple vehicles. To the best of the authors' knowledge, no standard methodology exists to define either a CV's mobility or an approach to assess it. In general, vehicle mobility is a subjective concept and mobility engineers have their own interpretations in defining it.

A CV's mobility strives to represent reality, but the complex mathematical calculations used to define and assess it do not always do so. Defining a CV's mobility using numerical values is cumbersome and the values tend to change when the vehicle and its

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2011	**Journal Article**	**13-01-2011 to 07-06-2011**

4. TITLE AND SUBTITLE
A Novel Approach for Combat Vehicle Mobility Definition and Assessment

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Macam Dattathreya; Harpreet Singh

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Wayne State University,5401 Cass Ave.,Detroit,Mi,48202

8. PERFORMING ORGANIZATION REPORT NUMBER
; #22314

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
#22314

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
For 2012 SAE WORLD CONGRESS

14. ABSTRACT
Mobility assessment for combat vehicles is often a great challenge for the military due to various subjective attributes. The attributes' characteristics vary significantly depending on the vehicle type and its operating environments such as terrain, weather, and human factors. A clear definition and relationship between multiple attributes including human factors is necessary to assess mobility. To the best of authors? knowledge, many existing mobility assessment techniques use complex analytical methods and focus on individual attributes. In this paper, for the first time, the authors propose a novel approach to define vehicle mobility and its influencing attributes using qualitative linguistic fuzzy variables, which are defined as having values between 0 and 1. The authors also propose a fuzzy logic mobility (FLM) model and a simulation approach to assess a combat vehicle's mobility.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

requirements change. In this situation, we need a generic independent common model for all types of vehicles and their mobility requirements. Numerical values can take different forms such that both engineers and non-engineers can understand and interpret them in a standard way. Instead of using complex empirical and analytical models with historical data, the authors propose to use an approximation and a heuristic technique with expert knowledge and natural linguistic information. By using linguistic variables such as low, low medium, high, and very high, one can paint a clear picture of a vehicle's mobility and its assessment. We cannot represent a subjective definition of mobility using mathematical and analytical techniques. Doing so, the definition of mobility becomes imprecise and vague.

In this paper, the authors propose a fuzzy logic approach for defining and assessing a CV's mobility using the fuzzy logic mobility (FLM) model. This approach has no data range limitations and is flexible enough to apply expert knowledge rules to assess mobility influencing attributes. In general, terrain characteristics, vehicle dynamics, and human factors are the major factors in defining and assessing a CV's mobility.

FUZZY LOGIC – AN OVERVIEW

Fuzzy logic is a soft computing technique that computes with words [3] to solve a vague real problem. Unlike Boolean logic, fuzzy logic [4] incorporates fuzzy set theory [5] to develop heuristic approximation reasoning to solve vague, non-deterministic problems.

In a conventional set, an element of the set either belongs to it or does not. In other words, an element has full membership in a set or no membership at all. In a fuzzy set, an element can have a degree of membership (μ). The degree ranges between 0 and 1. For example, an element "a "of a fuzzy set can have a μ of 0.8.

Formally, a fuzzy set is an ordered pair of elements with an appropriate membership degree within the range assigned for it. In other words, let "a" be an individual element in a universal set "S", a fuzzy set "F" can be derived from "S" using a set of ordered pairs $F = \{(a, \mu F(a)) \mid a \in S\}$ [5]. A membership function $\mu F(a)$ describes the numerical membership degree between 0 and 1 for example, 0.1, 0.12, 0.2, and .99.

Fuzzy logic is a cognitive or soft computing decision-making process. Control theory uses fuzzy logic to develop approximation-decision making techniques to control vague or subjective parameters of a system. Instead of analytical models using complex mathematics, fuzzy logic models systems based on expert knowledge of the system. Fuzzy logic describes the expert knowledge of a system, process, or situation using linguistic variables, i.e., words expressed in natural languages, e.g., hot, cold, very narrow, etc. In general, fuzzy logic describes systems or problems using fuzzy sets, a knowledgebase governing the constraints and the expert if-then rules to assess a set of variables of a system.

Many practical applications and systems have used fuzzy logic solutions. Some of the major applications include washing machines, rice cookers, image processing applications, anti-lock brake controls, and steering controls.

In general, fuzzy logic related research or solutions use a fuzzy logic system as a problem domain. Fuzzy logic systems [7] provide solutions using the following steps: fuzzification → expert rules application → rule- results aggregation → defuzzification. Mendel describes the details of fuzzy logic system in [7].

Each fuzzy set represents elements with different degrees of membership. One can determine an element's membership characteristics with respect to a fuzzy set using membership function plots that are triangular, trapezoidal, bell-shaped, or Gaussian. A triangular membership function is the simplest of all in terms of computation. Figure 1 represents the triangular membership function plot. In Figure 1,"s" represents the start range and "e" represents the end range of a given fuzzy set. Let $\mu F(a)$ be the membership grade represented on the y axis and "a" is the element's actual values on the x axis. At s and e, the membership grade of an element a is 0. Let c be the center point between s and e, where the membership grade of an element a is 1. The values between s and e, represent different grades of membership according to position on the triangular plot. The membership grades of an element using the triangular function plot shown in Figure 1. In (1), the membership grade function is described using the variables s, a, and c.

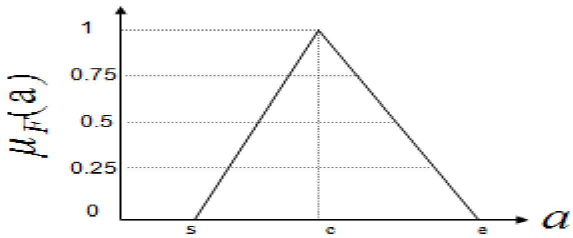

Figure 1 –Triangular membership function plot.

$$\mu_F(a) = \begin{cases} 0 & if \;\; a \le s \\ \dfrac{a-s}{c-s} & if \;\; s \le a \le c \\ \dfrac{s-a}{c-s} & if \;\; c \le a \le e \\ 0 & if \;\; a \ge e \end{cases} \tag{1}$$

FUZZY LOGIC MOBILITY MODEL AND ASSESSMENT ALGORITHM

This section describes the proposed Fuzzy Logic Mobility (FLM) model to define and assess a CV's mobility. The FLM consists of the following elements:

1. Fuzzy parameters
2. Fuzzy mobility assessment rules
3. Fuzzy mobility definition
4. Fuzzy mobility assessment algorithm

In general, tire pressure, weight, top speed, dash speed, and maximum speed of a CV are essential in assessing its mobility. For example, increased weight of the vehicle has an impact on how fast a vehicle can move while traversing through soft soil. Lower tire pressure and increased weight influences how the brake responds. The top speed of a CV is lower when it has low tire pressure and high vehicle weight. These statements are linguistic information about the mobility concepts and they do not have a numerical value at this point. The "top speed of a CV is lower when it has low tire pressure and high vehicle weight" is one example of an expert knowledge statement about brake assessment. Multiple expert rules can assess a CV's mobility. Fuzzy logic offers an approach to build on expert rules and obtain approximations using less computation.

The FLM uses simple expert knowledge based if-then rules to assess a CV's mobility. As mentioned earlier, mobility is a concept, which represents multiple entities depending on what entity you are trying to assess. For example, assessing range determination of a CV can be a mobility assessment in terms of 'range'. So, a standard 'mobility' term is used in this approach.

FUZZY PARAMETERS

Let A (1a) represent a set of vehicle types, for example, a type may be tracked-manned (TRM), wheeled-manned (WLM), tracked-unmanned (TRU), or wheeled-unmanned (WUM) i.e., *A = {TRM, TRU, WLM, WUM}.*

$$A = \{V_1, V_2, V_3,..., V_n\} \mid n > 0 \qquad (1a)$$

Let B (2) represent a set of vehicle operating environments. For example, an environment may be snowy (S), rainy (R), hot (H), cold (C), or windy (W) i.e., $B = \{S, R, H, C, W\}$.

$$B = \{O_1, O_2, O_3,..., O_n\} \mid n > 0 \qquad (2)$$

Let C (3) represent a set of terrains. For example, terrain may be paved (P), soft soil (SS), desert (D), river (R), or uneven terrain (UT) i.e., $C = \{P, SS, D, R, UT\}$.

$$C = \{T_1, T_2, T_3,..., T_n\} \mid n > 0 \qquad (3)$$

Let D (4) represent a set of attributes that influence vehicle mobility. For example, the attribute may be tire pressure (TP), weight (W), curb to curb diameter (C), top speed (TS), and dash speed (DS) i.e., D = {TP, W, C, TS, DS}.

$$D = \{A_1, A_2, A_3,..., A_n\} \mid n > 0 \qquad (4)$$

Let R (4a) represent a set of actual requirements for each of the attributes defined in (4). A_{1x} represents the requirement for an attribute A_1. For example, A_1 = tire pressure, the requirement of A_1 is to have 30 psi for a vehicle.

$$R = \{A_{1R}, A_{2R}, A_{3R},..., A_{nR}\} \mid n>0 \qquad (4a)$$

Let X (5) represent a set of ordered pairs of starting and ending numerical ranges for each of the attribute's (defined in (4)) numerical values. For example, A_1 represents an attribute of (4) (A_1 = tire pressure, for example), tire pressure has a numerical range of 0 to 40 psi (from Table 1). So $A_{1start} = 0$ and $A_{1end} = 40$.

$$X = \{(A_{1start}, A_{1end}), (A_{2start}, A_{2end}), (A_{3start}, A_{3end}),\ldots, (A_{nstart}, A_{nend})\} \mid n>0 \qquad (5)$$

Let us divide each attribute's range defined in (5) into nine equal parts and consider each part as a fuzzy set. Let Y (6) is a set of nine fuzzy sets per each attribute defined in (4). The fuzzy sets are obtained based on the ranges defined in (5) for each attribute. In set Y, f_{1A1} is one fuzzy set of an attribute A_1. For example, for a tire pressure attribute, 0 to 5.2 psi is one fuzzy set, i.e., f_{1A1}. Table 2 lists example fuzzy sets for the tire pressure attribute. For a consistent and standardized view for all the attributes, normalize each attribute's numerical range to map between 0 and 1 by dividing their actual numerical values by their maximum range value. For example, a 40 psi is the maximum tire pressure range as shown in Table1, therefore, a 20 psi tire pressure has value 20/40 = 0.5 and a 40 psi has value 40/40 = 1. We normalize any value greater than maximum value to1. For example, we represent an actual set of tire pressure values {10ps, 12ps, 22ps, 45ps, 36ps} using a normalized set {0.25ps, 0.3ps, 0.55ps, 1ps, 0.9ps}. Table 3 represents the normalized tire pressure range as an example.

$$Y = \{(f_{1A1}, f_{2A1}\ldots f_{9A1}), (f_{1A2}, f_{2A2}\ldots f_{9A2}),\ldots, (f_{1An}, f_{2An,}\ldots, f_{9An})\} \mid n>0 \qquad (6)$$

Let F (7) be a set of linguistic variables used to represent fuzzy sets.

$$F = \{L, LM, LH, ML, M, MH, HL, HM, H\} \qquad (7)$$

Based on expert knowledge of attributes, we label each fuzzy set of an attribute with an appropriate label from set F. Table 2 lists an example mapping for the tire pressure attribute. Let F_M (8) be a set of fuzzy sets mapped to linguistic variables.

$$F_M = \{(f_{1A1} \rightarrow L, f_{2A1} \rightarrow LM\ldots f_{9A1} \rightarrow H), (f_{1A2} \rightarrow L, f_{2A2} \rightarrow LM,\ldots f_{9A2} \rightarrow H),\ldots, \{(f_{1An} \rightarrow L, f_{2An} \rightarrow LM,\ldots, f_{9An} \rightarrow H)\} \qquad (8)$$

Table 1 –Example representing numerical ranges for each element of set D

Attribute	**Numerical range**
Tire pressure	0 to 40 psi
Weight	0 to 60,000 lbs
Top Speed	0 to 65 mph
Dash Speed	0 to 65 mph
Maximum Speed	0 to 80 mph

Table 2 – Example representing fuzzy set ranges for tire pressure attribute

Fuzzy set	**Numerical range**		**Fuzzy set**	**Numerical**
L (f_{1A1})	0 to 5.2 psi		MH (f_{6A1})	21.6 to 32 psi
LM (f_{2A1})	4.4 to 10.8 psi		HL (f_{7A1})	25.2 to 34.8 psi
LH (f_{3A1})	8.8 to 16 psi		HM (f_{8A1})	30.4 to 37.2 psi
ML(f_{4A1})	13.2 to 21.2 psi		H(f_{9A1})	35.6 to 40 psi
M (f_{5A1})	17.2 to 26.8 psi			

Table 3 – ***Example representing fuzzy set of normalized ranges for tire pressure attribute***

Fuzzy set	**Normalized numerical range**		**Fuzzy set**	**Normalized numerical range**
L	0 to 0.13ps		MH	0.54 to 0.8 psi
LM	0.11 to 0.27 psi		HL	0.63 to 0.87 psi
LH	0.22 to 0.4 psi		HM	0.76 to 0.93ps
ML	0.33 to 0.55 psi		H	0.89 to 1 psi
M	0.43 to 0.67 psi			

FUZZY MOBILITY DEFINITION

Let M_B be the assessed mobility output and let its range be from 0 to 1. We divide the range into nine equal parts to establish our fuzzy set. Let M_B (9) is a set of nine fuzzy sets for mobility. In set M_B, f_1 is one fuzzy set for mobility. We map the fuzzy sets into linguistic variables based on expert knowledge about mobility. For example, a mobility of 0 means low, a mobility of 1means high, a mobility of 0.5 means medium when compared to a defined requirement.

Mobility is a broader subjective term. For a CV, the mobility definition is a standardized way to represent certain vehicle dynamics. For example, we can represent maximum vehicle speed, fuel consumption, range (miles driven), and steering.

$$M_B = \{(f_1 \rightarrow L,\ f_2 \rightarrow LM, \ldots,\ f_9 \rightarrow H\} \quad (9)$$

Let M_{BA} (9a) be the set of mobility concepts for which an assessment is required. M_{Bx} may represent maximum vehicle speed, cruise range, fuel consumption, range (miles driven), or steering.

$$M_{BA} = \{M_{B1}, M_{B2}, M_{B3,}\ldots, M_{Bn}\} \mid n > 0 \quad (9a)$$

For a consistent and standardized view of mobility output values, we normalize the set of M_{Bx} so that their numerical range maps to between 0 and 1 by dividing their actual numerical values by their maximum range value. For example, if 400 miles is the maximum miles a CV can be driven (CV range), then a 200 miles range is given by 200/400 = 0.5 and 400 miles by 400/400 = 1. We normalize any value greater than the maximum value to1 (if for a reason some vehicles drive more than maximum miles defined). For example, an actual set of ranges {100 miles, 120 miles, 220 miles, 450 miles, and 360 miles} can be represented using a normalized set of {0.25, 0.3, 0.55, 1, and 0.9}.

FUZZY MOBILITY ASSESSMENT RULES

We build the assessment expert rules of a CV using expert knowledge about CV mobility and its influencing attributes. Let R_{MA} (10) be the set of fuzzy expert rules. We build rules per parameters defined in sets A, B, and C. For example, $R_1(V_1O_1T_1)$ is rule #1 for vehicle type V_1 (from set A), operating environment O_1 (from set B), and terrain T_1 (from set C). We construct the rules for $R_2\ldots, R_n$ similarly.

$$R_{MA} = \{ R_1(V_1O_1T_1), R_2(V_1O_1T_1),\ldots, R_n(V_1O_1T_1),\ldots., R_1(V_nO_nT_n),\ R_2(V_nO_nT_n),\ldots, R_n(V_nO_nT_n)\} \quad (10)$$

The rules can vary in number depending on the expert knowledgebase. See the example rule format below

$R_1(V_1O_1T_1)$: If $A_{1A} = L$ & $A_{1R}=L$ & $A_{3A} = H$ & $A_{3R} = H$ & $A_{2A} = L$ & $A_{2R} = L$ then $M_B = L$
$R_2(V_1O_1T_1)$: If $A_{2A} = L$ & $A_{2R}=L$ & $A_{3A} = H$ & $A_{3R} = H$ & $A_{2A} = L$ & $A_{2R} = L$ then $M_B = L$
$R_3(V_1O_1T_1)$: If $A_{2A} = L \mid\mid A_{3A} = H \mid\mid A_{2A} = L$ then $M = L$

Let us construct an example rule set using actual attributes. In the example below, TP_A = actual measured tire pressure and TP_R = requirement for tire pressure. Other attributes use a similar subscript style.

R_1 (TRM, S, P): If $TP_A = L$ & $TP_R = L$ & $DS_A = H$ & $DS_R = H$ & $TS_A = L$ & $TS_R = L$ then $M_B = L$
R_2 (TRM, S, P): If $TP_A = H$ & $TP_R = H$ & $DS_A = H$ & $DS_R = H$ & $TS_A = L$ & $TS_R = L$ then $M_B = H$
R_3 (TRM, S, P): If $TP_A = H \mid\mid DS_A = H$ then $M_B = H$

FUZZY MOBILITY ASSESSMENT ALGORITHM

This section describes the proposed CV mobility assessment algorithm using a fuzzy logic approximation approach. The algorithm reads as follows:

1. *Vehicle Type ← Get vehicle type from set A (1a)*
2. *Operating Environment ← Get operating environment from set B(2)*
3. *Terrain ← Get terrain from set C (3)*
4. *Mobility Assess Concept ← Get mobility assessment concept from set M_{BA}(9a)*
5. *List Attributes ← Get list of attributes to evaluate from set D (4)*
6. *List Requirements ← Get list of requirements for attributes from set R (4a)*
7. *List Rules ← Get appropriate rules for attributes from set R_{MA} (10)*

8. *List Attributes Measure ← Get actual measured values of attributes*
9. *Attributes Measure ← Normalized values (attributes measure)*
10. *For every attribute in attributes measure list*
11. *Fuzzified Inputs ← Fuzzification (attribute)*
12. *End for*
13. *U ← Apply fuzzy rules (rules, fuzzified_inputs)*
14. *U ← Aggregate results (Y)*
15. *W ← Compute mobility from defuzzification (Y)*

The fuzzification of inputs maps each of the crisp numerical values to an appropriate membership grade based on (8) for each of the attributes. This FLM uses triangular membership functions for both inputs and output. We arrange the triangular membership functions of all the fuzzy sets as shown in Figure 2. This allows us to obtain the proper membership grade of a given element across multiple fuzzy sets.

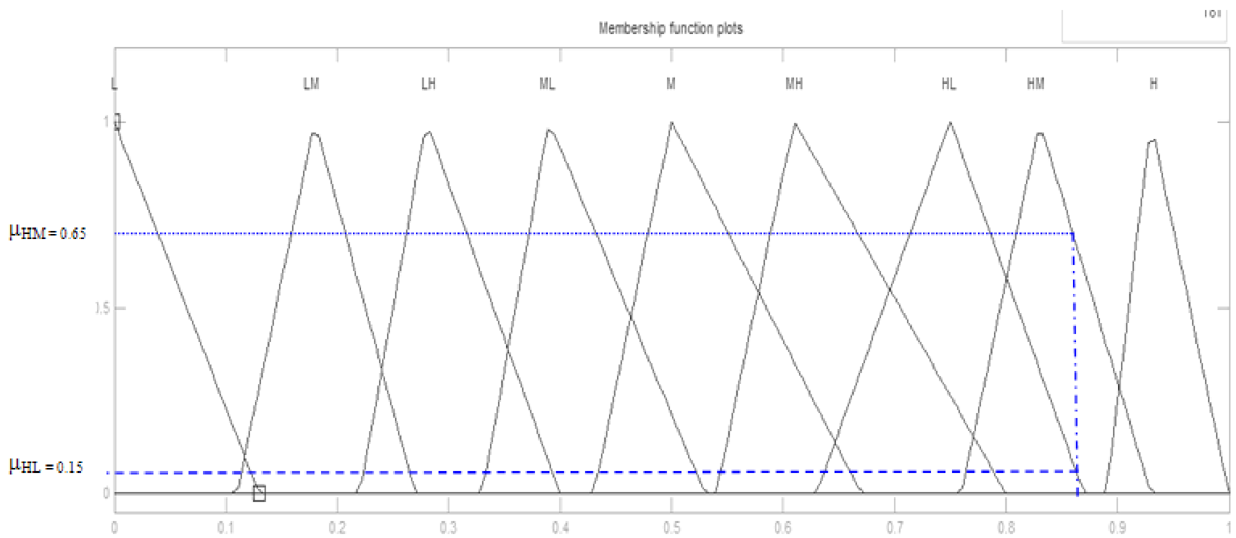

Figure 2 –Triangular membership function plot of all fuzzy sets of tire pressure attribute

For example, assume a tire pressure of 35 psi has a normalized value of 35/40 = 0.875. From Figure 2, the value of 0.875 falls between two membership functions HL and HM. When two membership functions overlap, use the maximum membership grade function. For example, 0.875 has a membership grade of 0.65 in HM and 0.15 in HL. In this situation, we use $max\ (\mu_{HL}, \mu_{HM}) = 0.65$.

Applying fuzzy knowledge based rules is a fuzzy reasoning or fuzzy inference process. We apply every rule to all the fuzzy inputs and then aggregate the results. The fuzzy rules determine how the algorithm decides to assign a fuzzy input to a fuzzy output space. When the "&" operator is used in a rule, the result of the rule application will be the minimum membership value from all the fuzzy inputs used in the rule. For example, assume the following membership grades are assigned for each input i.e., $\mu_{TP} = 0.3$, $\mu_{DS} = 0.4$, and $\mu_{TS} = 0.2$. With these membership grades, when a rule with "&" operator is applied, the result will be as (11).

$$TP \ \&\ DS \ \&\ TS = min\ (\mu_{TP}, \mu_{DS}, \mu_{TS}) \qquad (11)$$

When the " ||" operator is used in a rule, the result of the rule application will be the maximum membership value from all the fuzzy inputs used in the rule. For example, assume the following membership grades/values are assigned for each input i.e., $\mu_{TP} = 0.3$, $\mu_{DS} = 0.4$, and $\mu_{TS} = 0.2$. With these membership grades, when a rule with "||" operator is applied, the result will be as (12)

$$TP \ //\ DS \ ||\ TS = max\ (\mu_{TP}, \mu_{DS}, \mu_{TS}) \qquad (12)$$

From (11), the result of a rule is min (0.3, 0.4, 0.2) = 0.2. From (12), the result of a rule is max (0.3, 0.4, 0.2) = 0.4. Similarly, we apply all the rules established for a given assessment. Figure 3 depicts an example of aggregated output distribution.

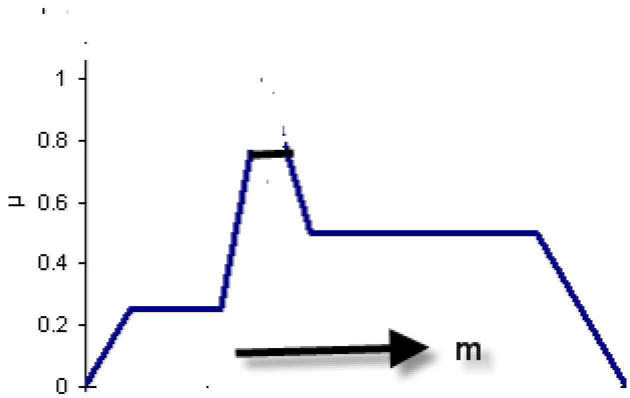

Figure 3 –Aggregated output distribution for a mobility assessment example.

Defuzzification uses the aggregated output distribution (Figure 3), applies the centroid function (13), and gets a crisp output number. The number obtained from the defuzzification process is the CV's mobility assessment number. In the next section, we simulate an example CV's mobility assessment and describe its results. In (13), M is a defuzzified value, μ (m) is the aggregated membership function obtained from Figure 3, and m is the output variable.

$$M = \frac{\int \mu(m)m\, dx}{\int \mu(m) dx} \qquad (13)$$

SIMULATION / RESULTS/DISCUSSIONS

Consider an example of finding a given CV's range based on a set of parameters that directly influence range. Range is the number of miles a vehicle drives before it exhausts its fuel. In practice, the actual miles driven for a vehicle depends on the following vehicle characteristics: vehicle gear, vehicle speed, fuel capacity, engine speed, tractive-force, total electric power requirement, and brake specific fuel consumption (BSFC),

In general, a CV's range is determined based on mathematical calculations. Using an FLM approach, mobility is defined using values between 0 and 1. For simulation example purposes, we use vehicle speed (VS), fuel capacity (FC), required power (RP), and fuel consumption map (FM) as inputs. For simplicity, this simulation assumes a default value for vehicle gear, engine speed, and tractive-force values. The main purpose of this approach is to demonstrate an FLM approach to assess mobility for a CV.

This simulation assesses a CV's range as the mobility output and will be represented with a value between 0 and 1. The inputs and the output use normalized values.

Based on expert knowledge about all the inputs in evaluating vehicle range, Figure 4 represents membership functions for fuzzy sets of inputs and Figure 5 represents output membership functions.

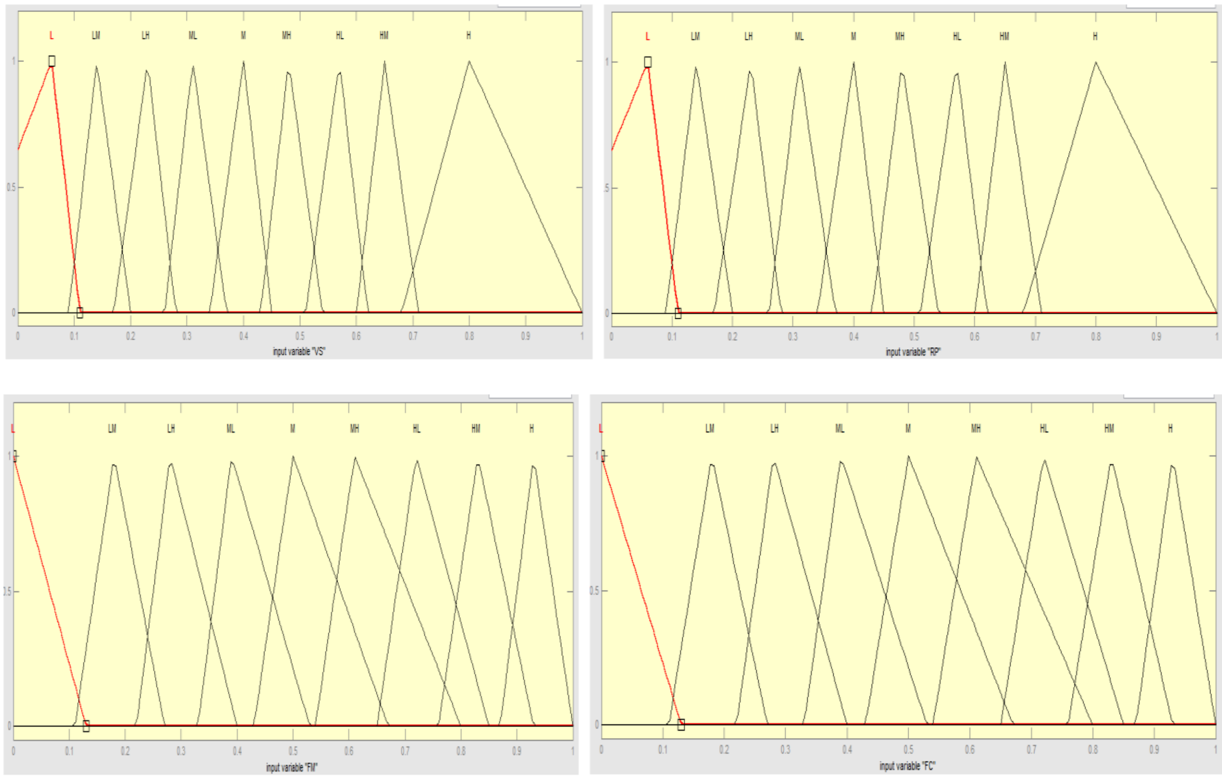

Figure 4 –Triangular membership function plots of all fuzzy sets of range inputs

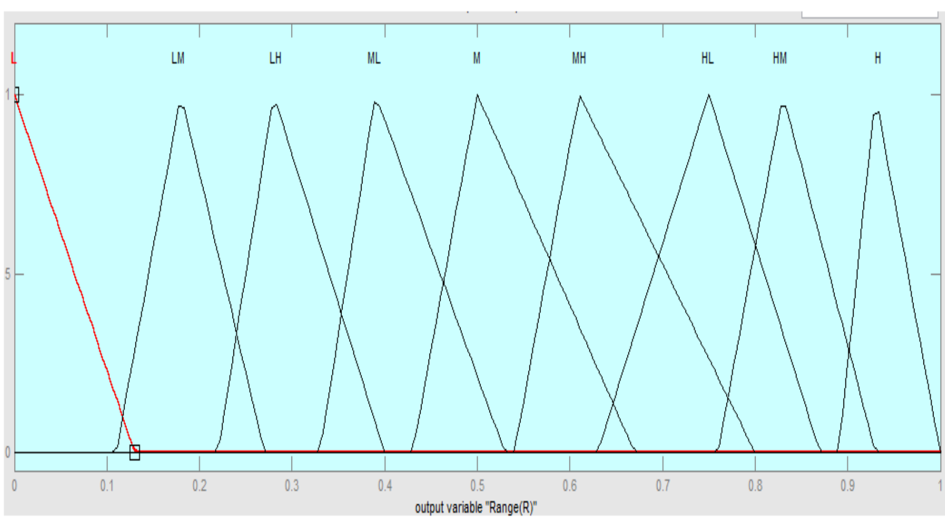

Figure 5 –Triangular membership function plots of all fuzzy sets of range output (Mobility)

Figure 6 represents sample fuzzy expert rules to assess a CV's range. These rules are a sample and do not represent the whole rule set needed to evaluate range. Figure 7 describes an approach that we can use for an FLM.

1. (VS==H) & (RP==L) & (FM==L) & (FC==H) => (Range(R)=H) (1)
2. (VS==H) & (RP==L) & (FM==LM) & (FC==H) => (Range(R)=HM) (1)
3. (VS==H) & (RP==L) & (FM==LH) & (FC==H) => (Range(R)=HL) (1)
4. (VS==L) & (RP==LM) & (FM==LM) & (FC==LH) => (Range(R)=LH) (1)
5. (VS==MH) & (RP==MH) & (FM==MH) & (FC==MH) => (Range(R)=ML) (1)
6. (RP==H) & (FM==H) & (FC==L) => (Range(R)=L) (1)
7. (RP==HM) & (FM==LM) & (FC==LM) => (Range(R)=LM) (1)
8. (RP==HM) & (FM==LM) & (FC==LH) => (Range(R)=LH) (1)

Figure 6 –Sample fuzzy expert rules for assessing mobility

Figure 7 represents the fuzzification of inputs, aggregation of rules results, and defuzzification using a centroid function (13). From Figure 7, the normalized range obtained per the established rules is 0.841, the actual range falls into the "H" fuzzy set of mobility output. The de-normalized value of range is 0.841 * 400 = ~ 332. This simulation uses 400 miles as the value for maximum range of a vehicle for pre-established inputs.

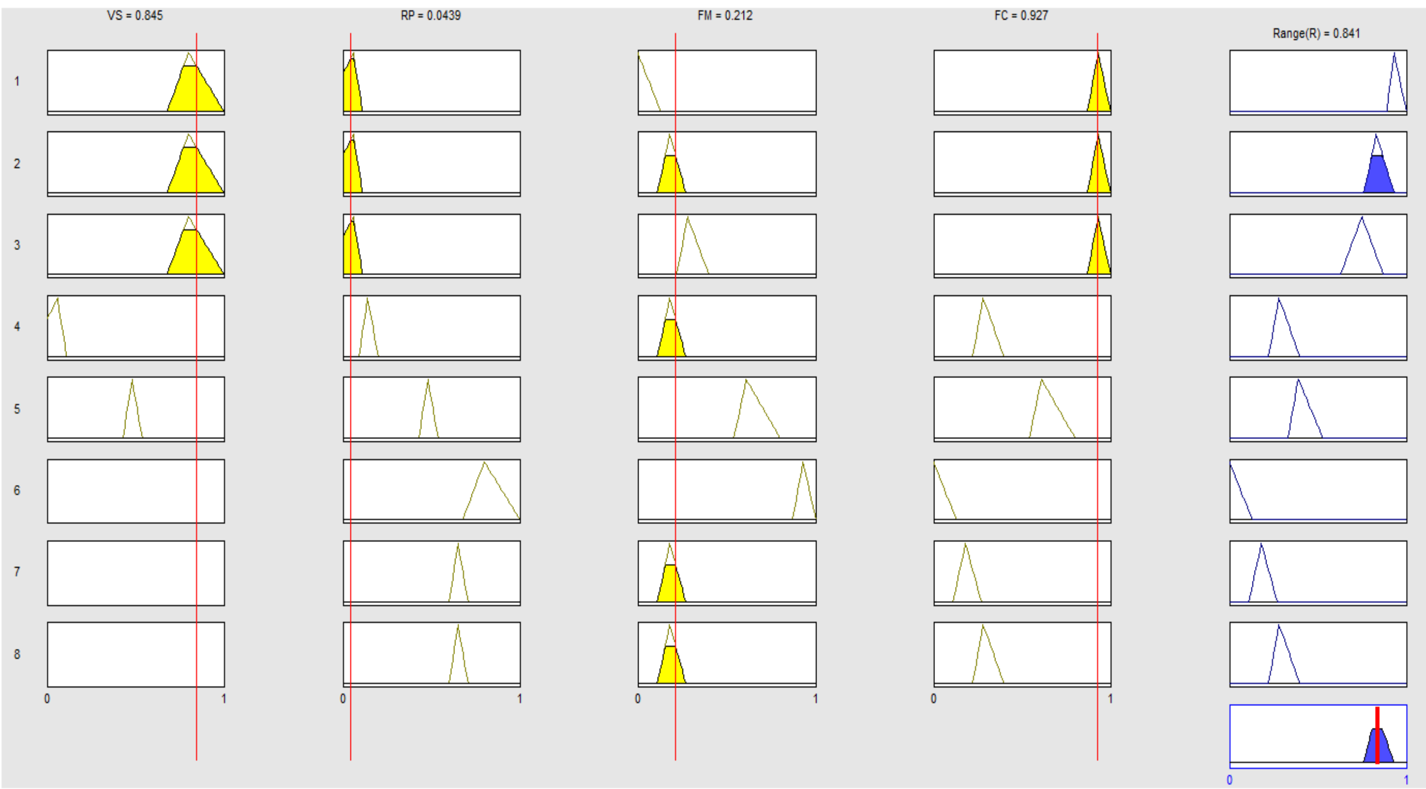

Figure 7 –Fuzzification, aggregation of rules result, and defuzzification for assessing mobility using FLM

CONCLUSION

In this paper, the authors introduced a new approach for assessing the mobility of a CV using an FLM. The fuzzy logic approach provides approximation techniques that define subjective mobility using linguistic labels between the values of 0 and 1. The FLM requires less computational effort and minimizes the time to obtain a closer approximation of a CV's mobility. The FLM builds the mobility assessment system based on expert knowledge of the mobility and its influencing attributes. The FLM represents all the

attributes including both inputs and outputs using normalized values; this helps provide a standard range for all variables of the mobility assessment system. The FLM provides a standard definition for mobility using linguistic labels such as high, low, and medium. The linguistic labels avoid conflicting interpretations.

The FLM reduces the use of complex mathematical equations to assess the mobility of combat vehicles. If the FLM has enough expert rules, then it is as good a method for at assessing mobility as using complex equations. One can use custom fuzzy logic software or proprietary simulation tools such as Fuzzy Logic Toolbox and Simulink software for MATLAB, FuzzyTECH, and XPertRule to build and simulate an FLM model. The FLM is in its initial stages of research. Future work will automate model definition using rules optimization features to enhance and simplify simulation of the FLM assessment approach.

DISCLAIMER

Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors- expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.

REFERENCES

1. Patrick, N., Reid, A., Jones, R., and Shoop, A., “A Virtual Evaluation Suite for Military Ground Vehicle Dynamic Performance and Mobility,” SAE Technical Paper 2002-01-3049, 2002, doi: 10.4271/2002-01-3049.
2. Ahlvin, D., Haley, P., “NATO Reference Mobility Model Edition II, NRMM II User’s Guide,” Technical Report Number GL-92-19, U.S. Army Waterways Figure 9, CRREL Instrumented Vehicle (CIV) Rolling on Snow (top) and Finite Element Model Experiment Station, Corps of Engineers, Vicksburg, MS, December 1992.
3. Zadeh, L. A., “Fuzzy Logic = Computing with Words," IEEE Trans. Fuzzy Systems: 4(2), 1996, May 1996.
4. Zadeh, L.A., “Is There a Need for Fuzzy Logic”, Information Sciences.178: 2751-2779, 2008.
5. Zadeh, L. A., “Fuzzy Sets,” Inform. Contr..8(3):338-353, 1965.
6. Bezdek, J. C., “Fuzzy models—what are they, and why”, IEEE Trans. Fuzzy Sys. 1(1):1–6, 1993, Feb. 1993.
7. Mendel, J. M., “Fuzzy logic systems for engineering: A tutorial," Proc. of the IEEE, Special Issue on Fuzzy Logic in Engineering Applications: 83(3):345–377, 1995, March 1995.